Further Development of the PCRTM Model and RT Model Inter Comparison

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Motivation

- Extend the existing PCRTM to include solar reflection contribution.
- Generate robust cloud/aerosol LUTs for fast radiative transfer simulation.
- Training radiance data for IASI, NASTI, CrIS, AIRS, and SHIS instruments for PC based fast radiative transfer simulation.
- Apply the new results to retrieval applications.

Part I: Cloud/Aerosol LUTs Generation

- The strategies we used to get robust LUTs…

Tool: Modified DISORT

- Start from version 2, DISORT needs the full phase function Legendre expansion to reconstruct the actual phase function for single and secondary scattering calculation. For some ice clouds, hundreds or thousands of Legendre polynomial expansion terms are required.
- One has to determine how many stream should be used in DISORT. In general, larger stream number gives better results but increase the computational burden ($t \propto N^3$).

δ-M Transformation

- The original phase function may be expanded as $P(\cos\theta)=\sum_{n=0}^{\infty}(2n+1)g_n L_n(\cos\theta)$

- In the δ-M transformation, the phase function is approximated by

$$P^*(\cos\theta)=2f\delta(1-\cos\theta)+(1-f)\sum_{n=0}^{2N-1}(2n+1)g'_n L_n(\cos\theta)$$

$$g'_n=\frac{g_n-f}{1-f}, \qquad (n=0,1,\ldots,2N-1)$$

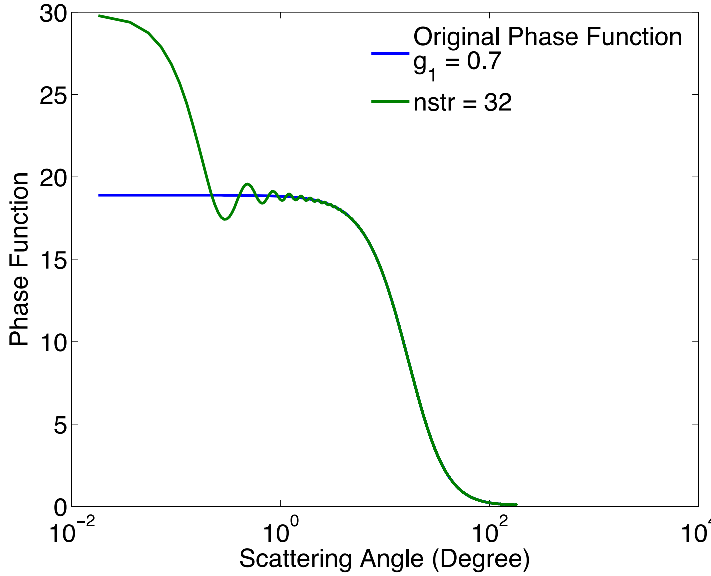
$$f=g_{2N}$$

- δ-M phase function

$$P'(\cos\theta)=\sum_{n=0}^{2N-1}(2n+1)g'_n L_n(\cos\theta)$$

- Error in δ-M transformation

$$\Delta P=\sum_{j=2N+1}^{\infty}(2j+1)(g_j-g_{2N})L_j(\cos\theta)$$



δ-M Transformation

The δ-M transformation also includes the scaled optical depth and scaled single scatter albedo:

$$P^*(\cos\theta) = 2f\delta(1-\cos\theta) + (1-f)\sum_{n=0}^{2N-1}(2n+1)g'_n L_n(\cos\theta)$$

$$g'_n = \frac{g_n - f}{1-f}, \qquad (n = 0, 1, \ldots, 2N-1)$$

$$f = g_{2N}$$

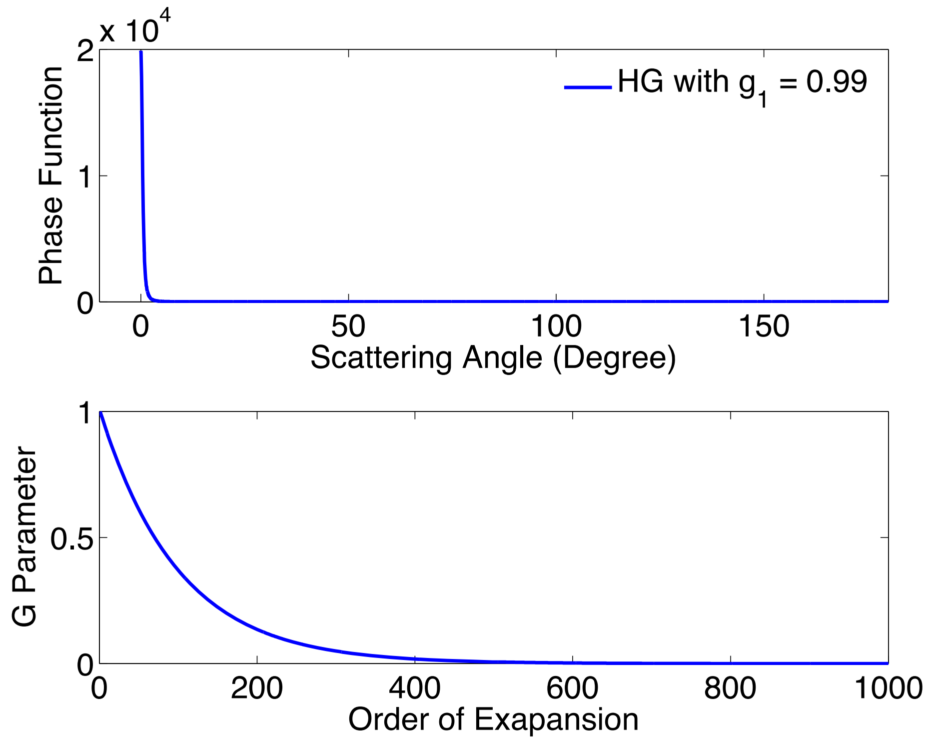
$$P'(\cos\theta) = \sum_{n=0}^{2N-1}(2n+1)g'_n L_n(\cos\theta)$$

$$d\tau' = (1-\omega f)d\tau \qquad \omega' = \frac{1-f}{1-\omega f}\omega$$

Identical form of the radiative transfer equation is obtained if one replaces P, τ, ω with P’, τ□, ω□, respectively.

δ-M Transformation

- δ-M Transformation
  - Take advantage of the fact that the higher-order Legendre polynomial expansion terms contribute primarily to the δ-function-like forward peak.
  - It is very efficient to reduce error which is caused by using limited number of streams.
- Disadvantage:
  - It misrepresents single scattering rather badly.
  - For some ice clouds, hundreds or thousands of Legendre polynomial expansion terms are required to obtain the exact phase function for single-scattered intensity correction.



Intensity Correction in DISORT

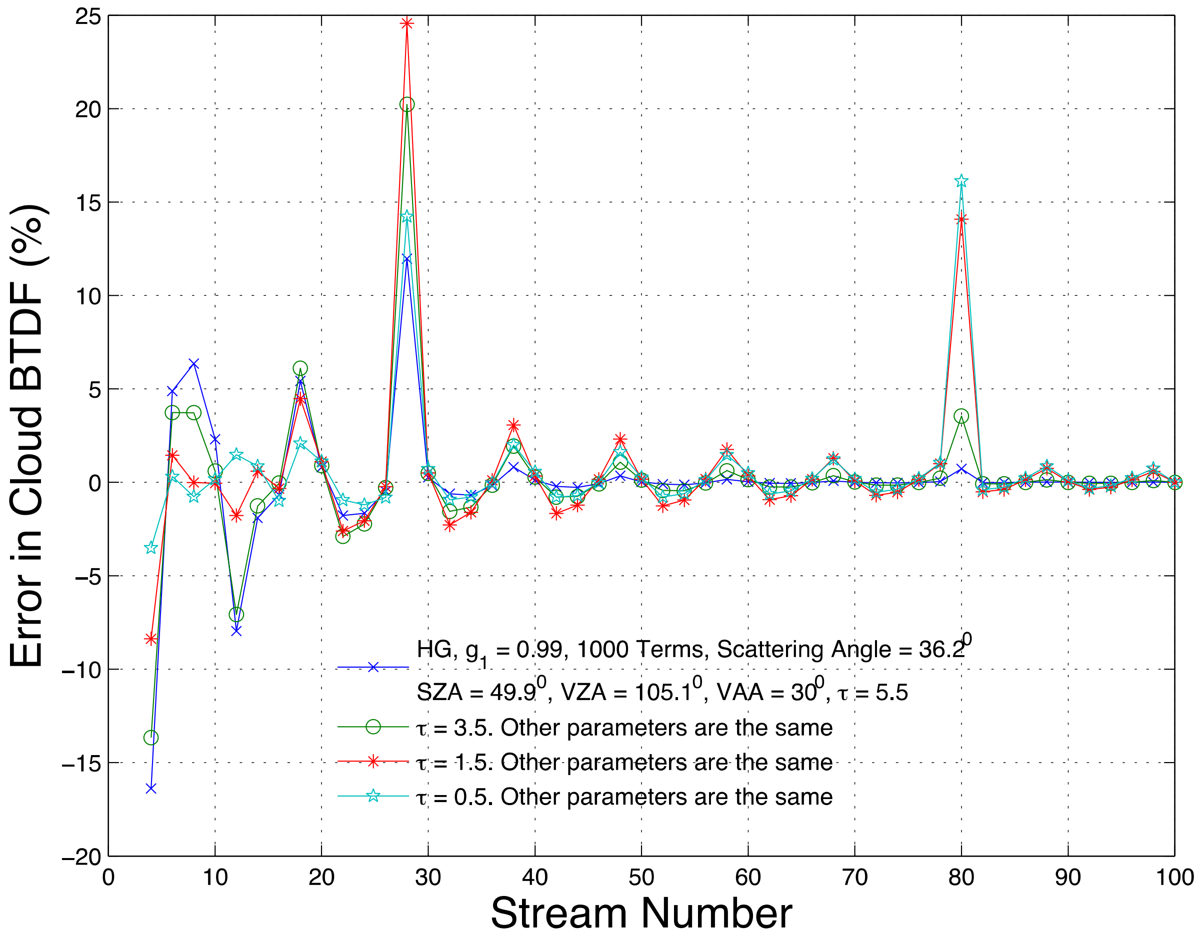
- TMS method:
  - It subtracts the single-scattered intensity from the δ-M phase function (calculated from just 2N terms), then add back the τ-scaled intensity based on the 'exact' phase function (calculated from all available terms in the Legendre expansion) and the unscaled single scattering albedo.
- IMS method:
  - It is an improved version of TMS method which intended to correct for errors in the aureole (near-forward-scattering) region by approximating secondary or higher orders of scattering.

- Remain Problems:
  - The DISORT called 'exact phase function' or 'actual phase function' is calculated from the available Legendre expansion coefficients. It may have big difference with the 'real phase function' for strongly anisotropic scattering with limited terms of expansion coefficients.
    - Over thousands terms needed
    - Compare with radiance calculation using real full phase function (Monte-Carlo)
  - No intensity correction for multiple scattering.

Our Strategy: Modified DISORT

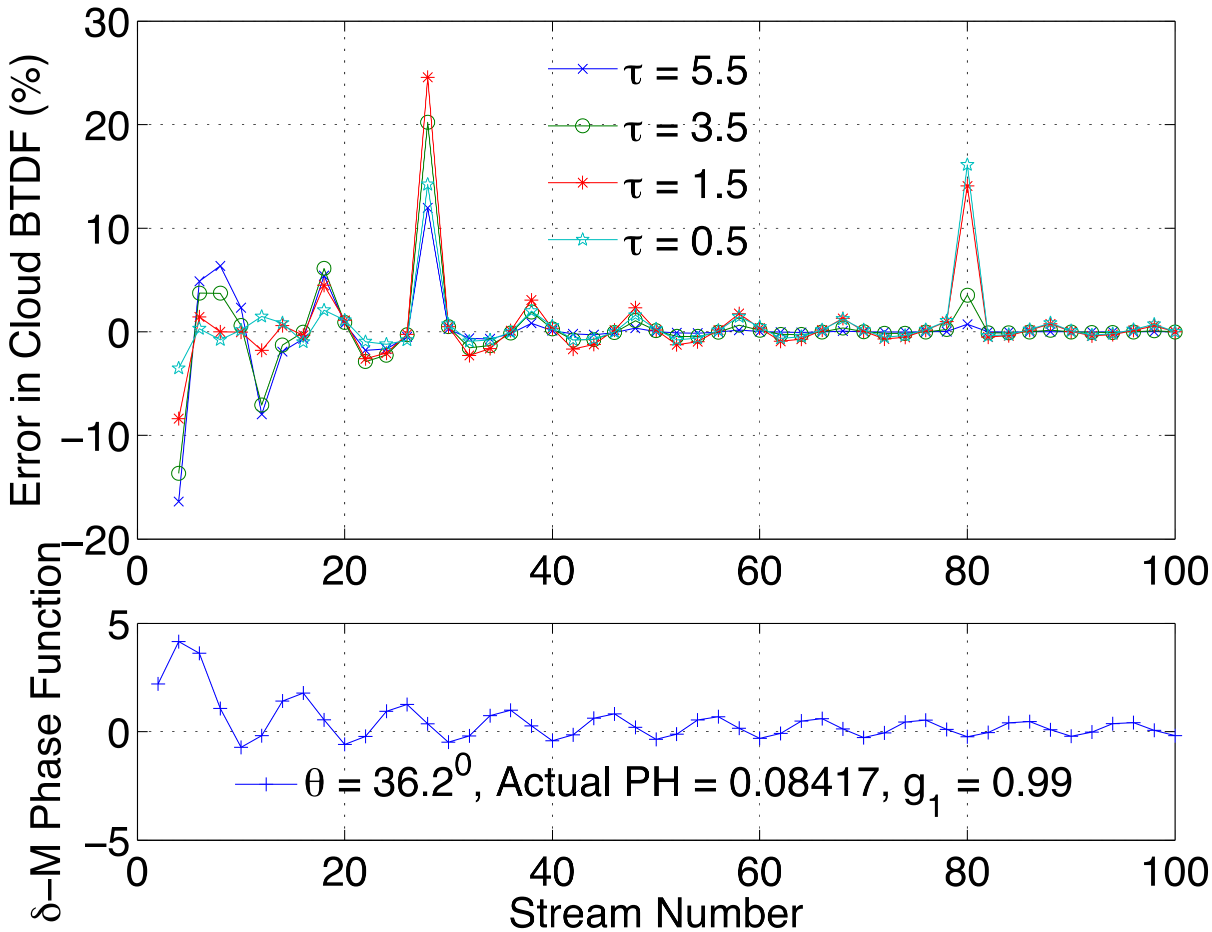
- **Real phase function is provided directly,** not reconstructed from Legendre coefficients as does in original DISORT, for single and secondary scattering.
- Using our **neighborhood watch strategy** for multiple scattering calculation.
  - **Less than 20 Legendre coefficients** are enough to get very high accuracy which original DISORT may require hundreds streams to get the same accuracy.

Original DISORT: Stream Number Dependence



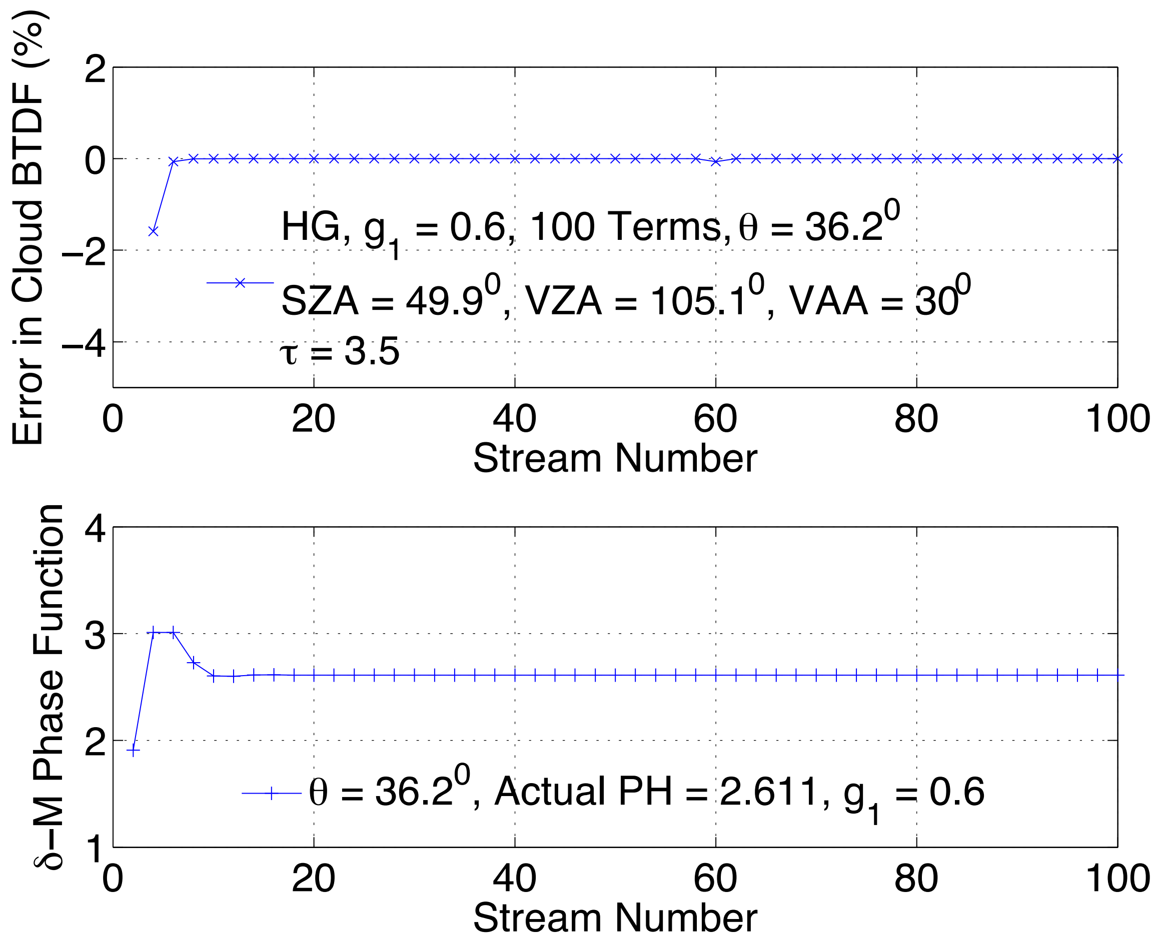
The so-called 'actual phase function' was reconstructed from 1500 phase moments, which was constant in all the calculations. The multiple scattering induced oscillation caused either by the δ-M phase function or quadrature angles. Both of them change with stream number.

Original DISORT: Stream Number Dependence vs δ-M Phase Function



The oscillation/fluctuation is correlated with the δ-M phase function!
(The oscillation behavior is different from single scattering induced oscillation).

Original DISORT: Stream Number Dependence vs δ-M Phase Function

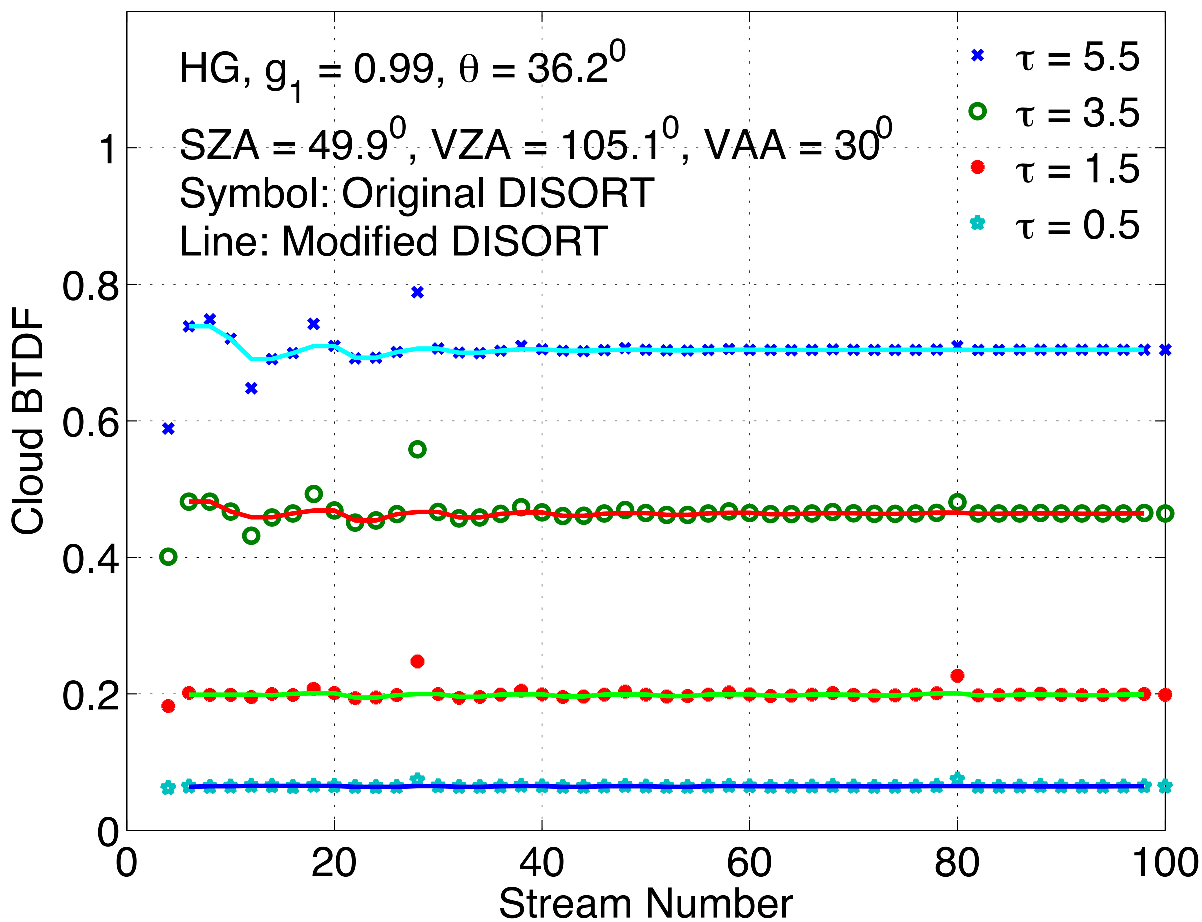


The quadrature angle changed, but the radiance still kept constant.

Our Strategy: Modified DISORT

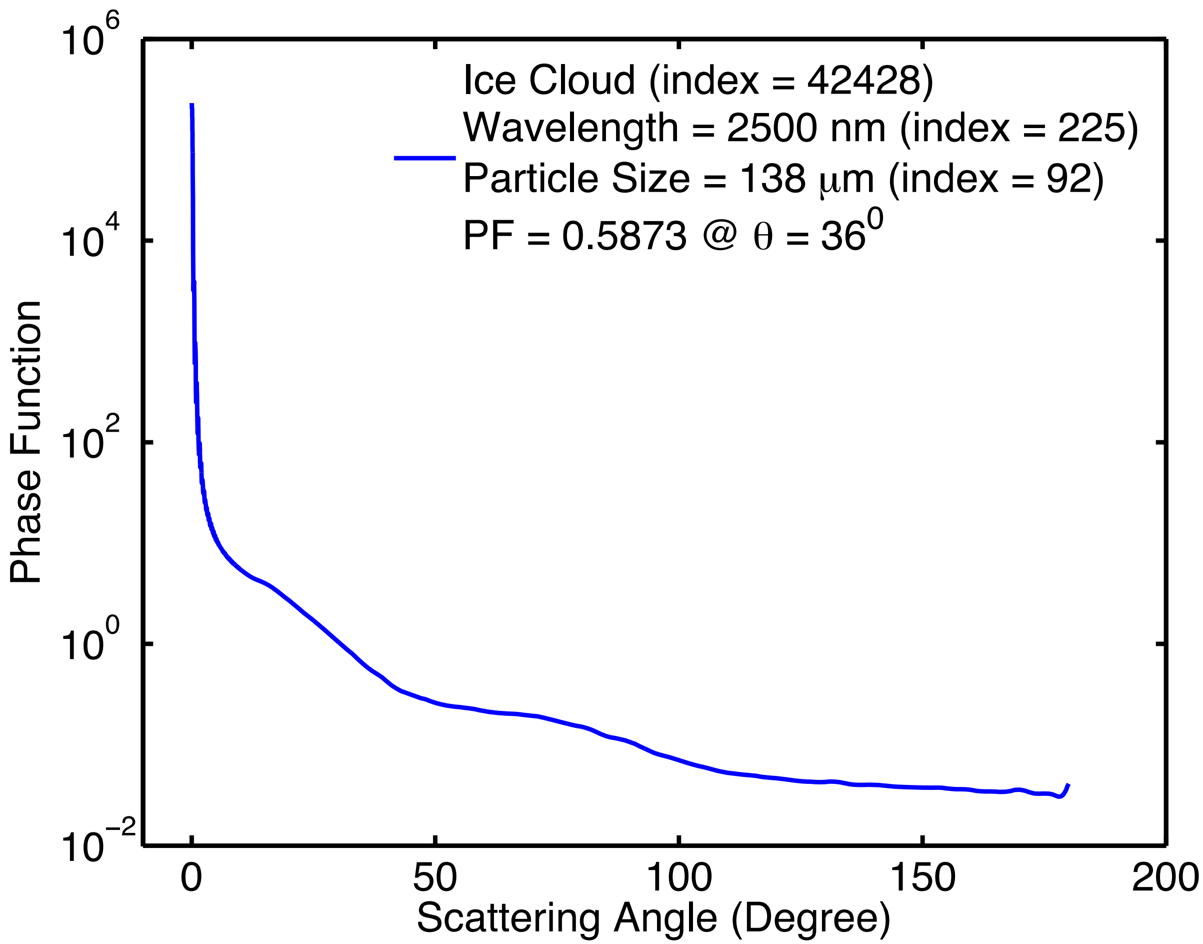
- To get solid results for ice cloud LUTs, we used:
  - **Real phase function** for single and secondary scattering.
  - **Neighborhood Watch Strategy:** compare neighboring δ-M phase function for multiple scattering simulation
    - If $|PF_{2N}-PF_{2N-2}|>0.01$ or $|PF_{2N}-PF_{2N+2}|>0.01$ then DISORT will be called at these three stream numbers and the medium output will be taken as the final result.
    - If $|PF_{2N}-PF_{2N-2}|<0.01$ or $|PF_{2N}-PF_{2N+2}|<0.01$ then DISORT is called at stream number 2N only.
  - Use this method, we can get very accurate results using very small stream number (**< 20 or even 10**) for highly anisotropic scattering cases. Thus greatly improve the computation efficiency.

Modified DISORT: Results Using Our Strategy

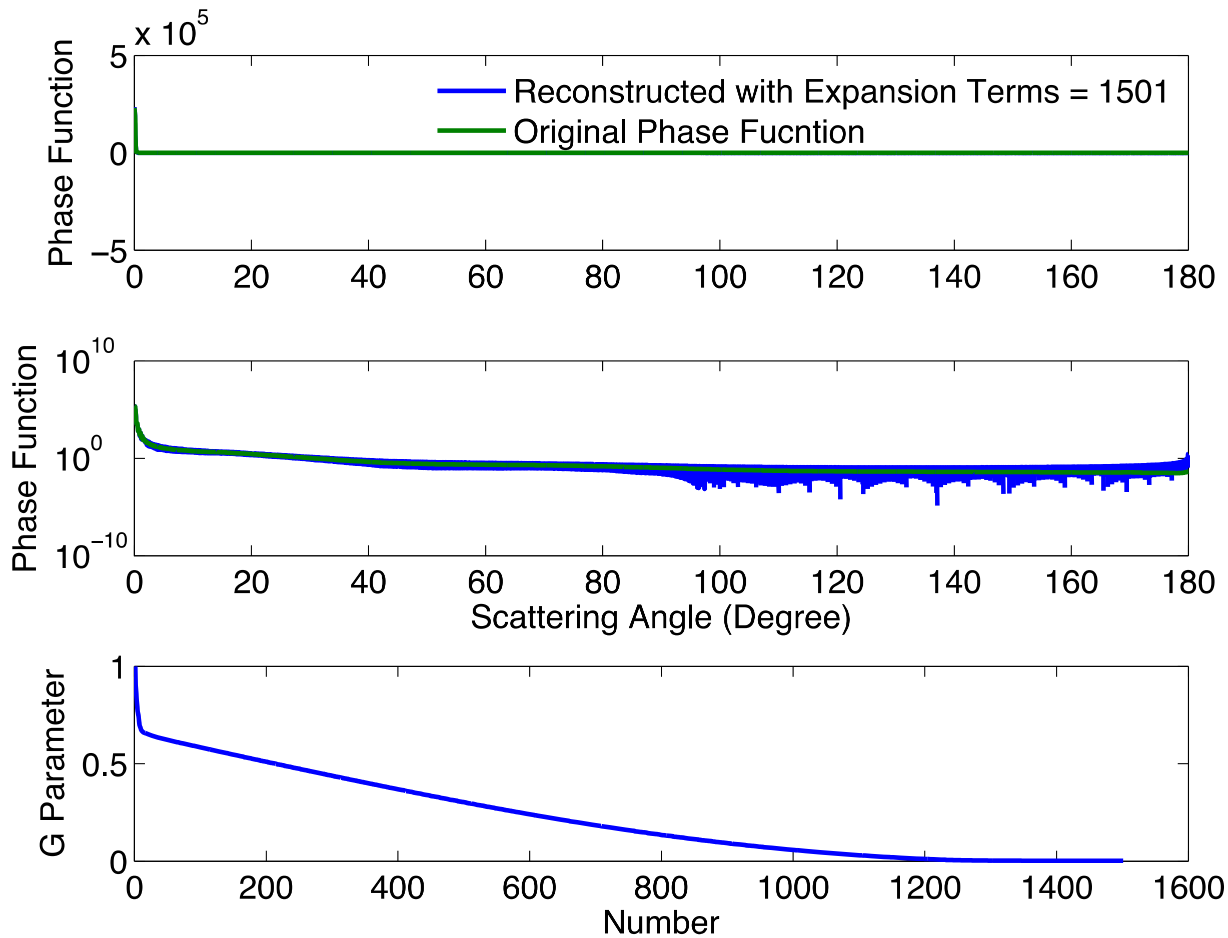


For this tough case (g_1 = 0.99), good results can be obtained using less than 20 streams.

Example from Ice Cloud

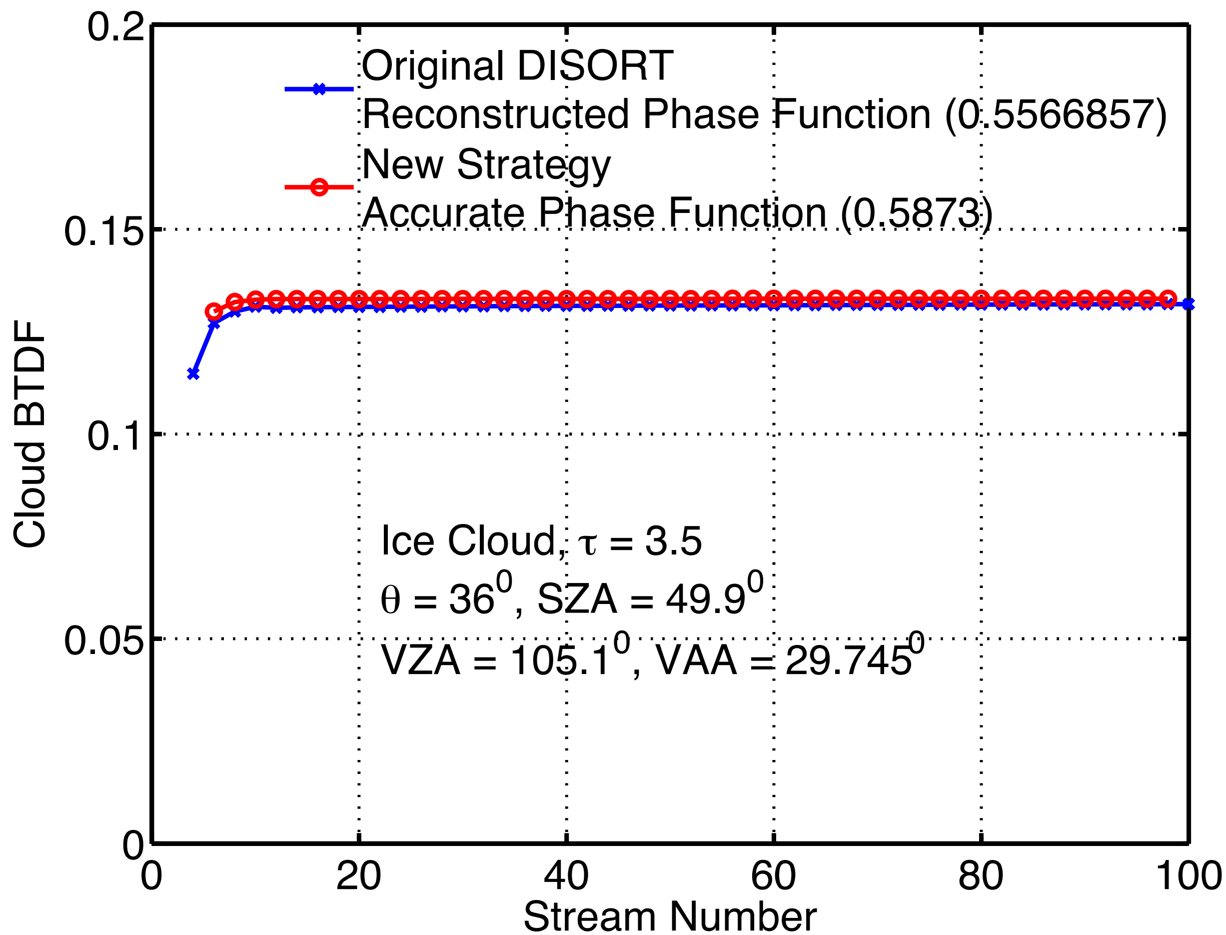


Example from Ice Cloud



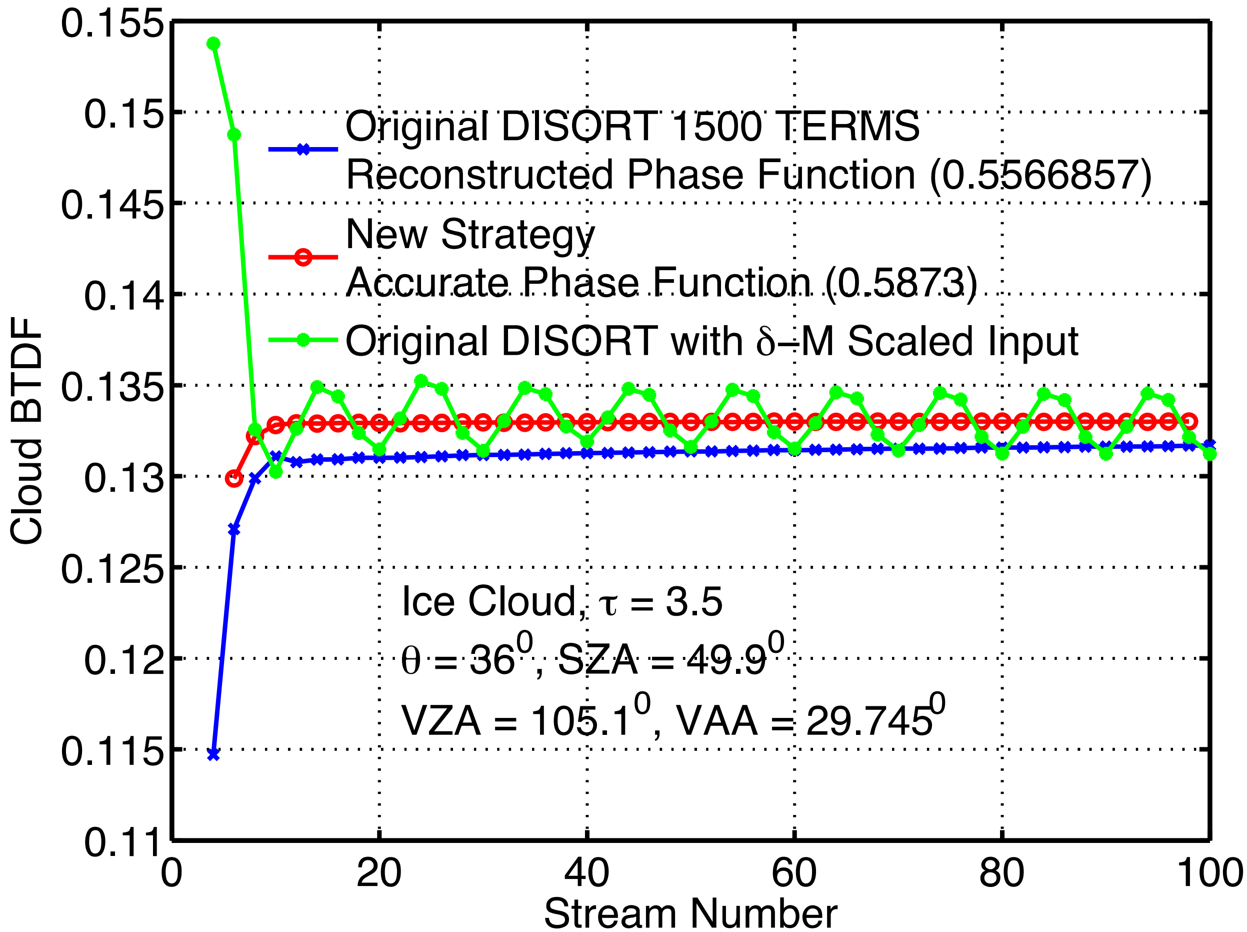
Even with 1500 phase moments, the reconstructed 'actual phase function' is still different from the 'real phase function', especially at large scattering angles.

Example from Ice Cloud



If number of phase moments is less than 1400, much worse results are obtained using original DISORT. Using our new strategy, less than 20 phase moments are enough to get high accurate results.

Example from Ice Cloud



Modified DISORT: almost constant when stream number is larger than 10 (0.13295± 0.00005).
Original DISORT with 1500 phase moments: slightly increase with stream number (0.1311 to 0.1317).
Original DISORT with δ-M scaled inputs: oscillate around the true value with stream number.
Modified DISORT gives much better results at very small stream number!

Summary of PART I

- The cloud/aerosol bidirectional reflectance and transmittance have been carefully calculated using the modified DISORT under over 10 millions of diverse conditions with varying cloud particle size, optical depth, wavelength, satellite viewing direction, and solar angles.
- The obtained results were compressed significantly using principal component analysis and used in the mono domain radiance calculation (part II of this work).
  - More details may be found in
    - X. Liu, Q. Yang, W. Wu, S. Kizer, P. Yang, Z. Jin, B. Wielicki, and R. Baize, *Progress on Fast and Accurate Radiative Transfer Model Development in the Presence of Multiple Scattering Clouds and Aerosols*, CLARREO SDT Meeting, Lawrence Berkeley National Laboratory, April 28-30th, 2015

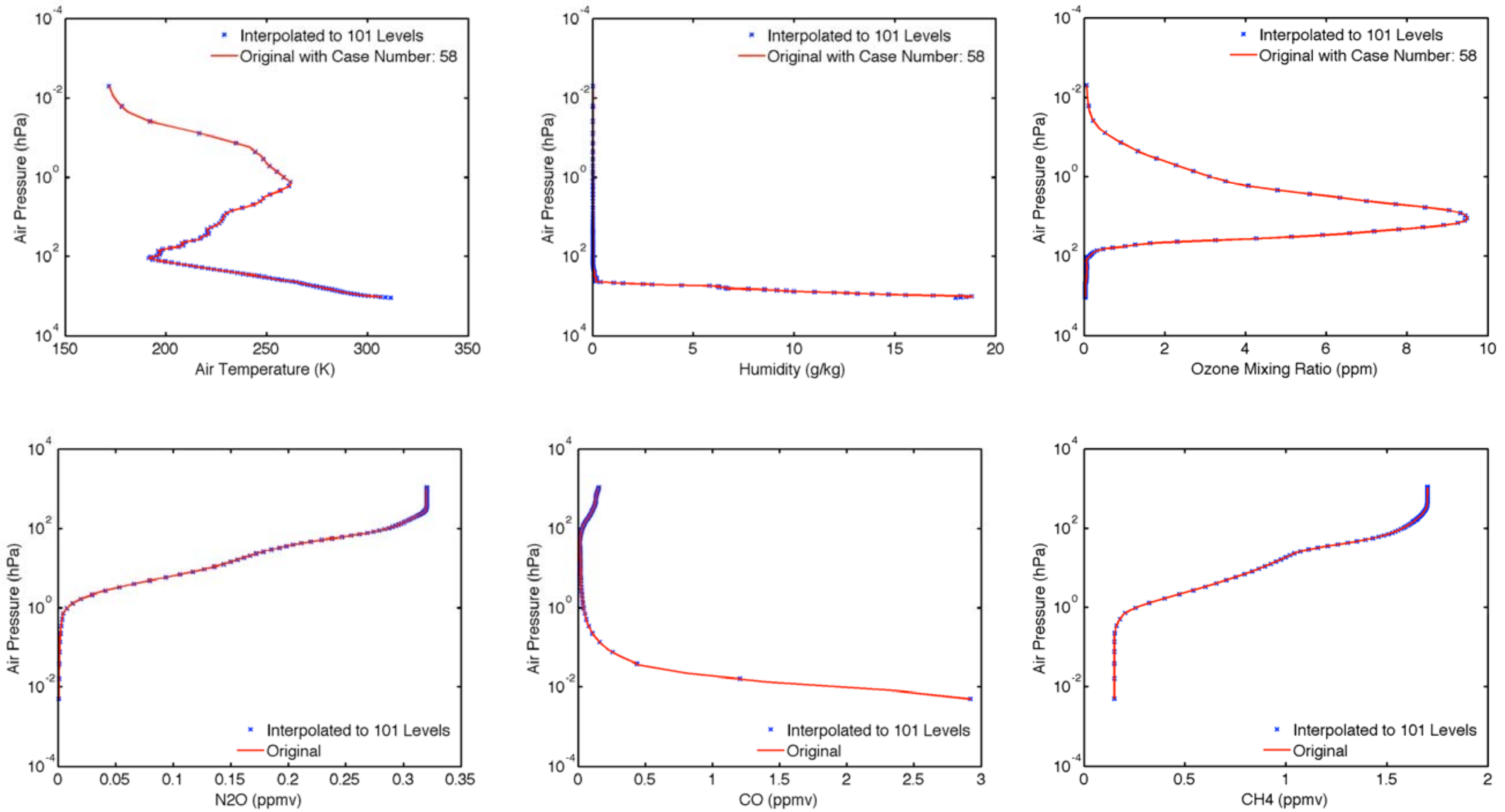
PART II: TRAINING

- A. Mono Domain Radiance Calculation
  - We used 1352 different atmosphere profiles, each of them has different surface skin temperatures and surface pressures in our training.
  - Different surface emissivity spectra were derived from ASTER database and emissivity models. Some artificially generated emissivity spectra were also used to account for diverse surface types of the earth.
  - Concentrations of sixteen trace gases were varied systematically in the training and the remaining trace gas contributions were accounted for as a fixed gas.
  - Both clear and cloudy skies were included in this work.
  - Both thermal and solar contribution were included.
- B. Channel Domain Radiance Calculation
  - Channel domain radiances were calculated from the obtained mono radiances and the corresponding apodization function for each instrument.
- C. Training
  - The obtained data were trained using PCRTM training procedure.
  - The nonlocal thermal equilibrium (NLTE) induced radiance change was included for daytime conditions.
  - We have updated the PCRTM model for instruments such as IASI, NASTI, CrIS, AIRS, and SHIS.
- D. Results
  - The training results show that the PCRTM model can calculate thousands of channel radiances by computing only a few hundreds of mono radiances. This greatly increased the computation efficiency since we do not need to calculate the millions of mono radiances and do the convolution process.
  - The results from fast PCRTM_Solar simulation were compared to the instrument observed data. The simulated results were excellently agreed with the observations (see Part III).

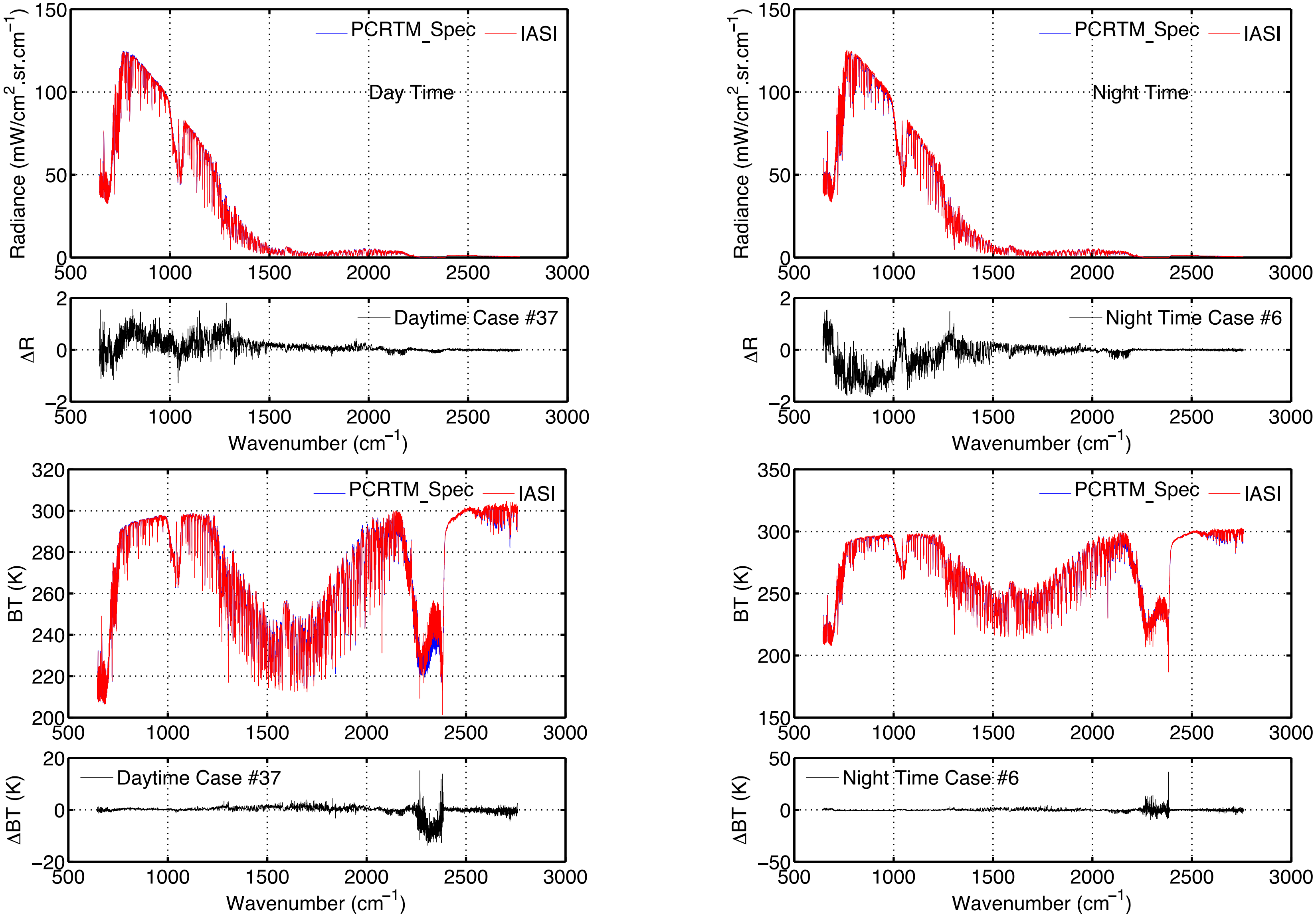
PART III: Inter Comparison

- The high quality radiosonde data were provided by GRUAN (The GCOS Reference Upper Air Network). The dataset includes 76 collocation events between GRUAN sondes and IASI observations.
  - The data include:
    - Latitude, Longitude, SZA, SAA, VZA, VAA, Surface Air Pressure, Surface Air Temperature, Surface Skin Temperature, Surface Specific Humidity, Cloud Area Fraction, Land Area Fraction, Surface Emissivity, Air Temperature, Air Humidity.
    - Concentration for the following 23 gases: CO2, Ozone, N2O, CO, CH4, O2, NO, SO2, NO2, NH3, HNO3, OCS, N2, HCN, C2H2, HCOOH, C2H4, CH3OH, CCL4, CF4, F11, F12, and F22.
- The measured collocation IASI radiances provided by Stephen A. Tjemkes.
- We first compare the results without NLTE since the data we obtained for other RT models did not include NLTE.
- Then we show how solar contribution and NLTE, which is included in PCRTM_Solar, increases the accuracy of the RT model in the high wavenumber range.

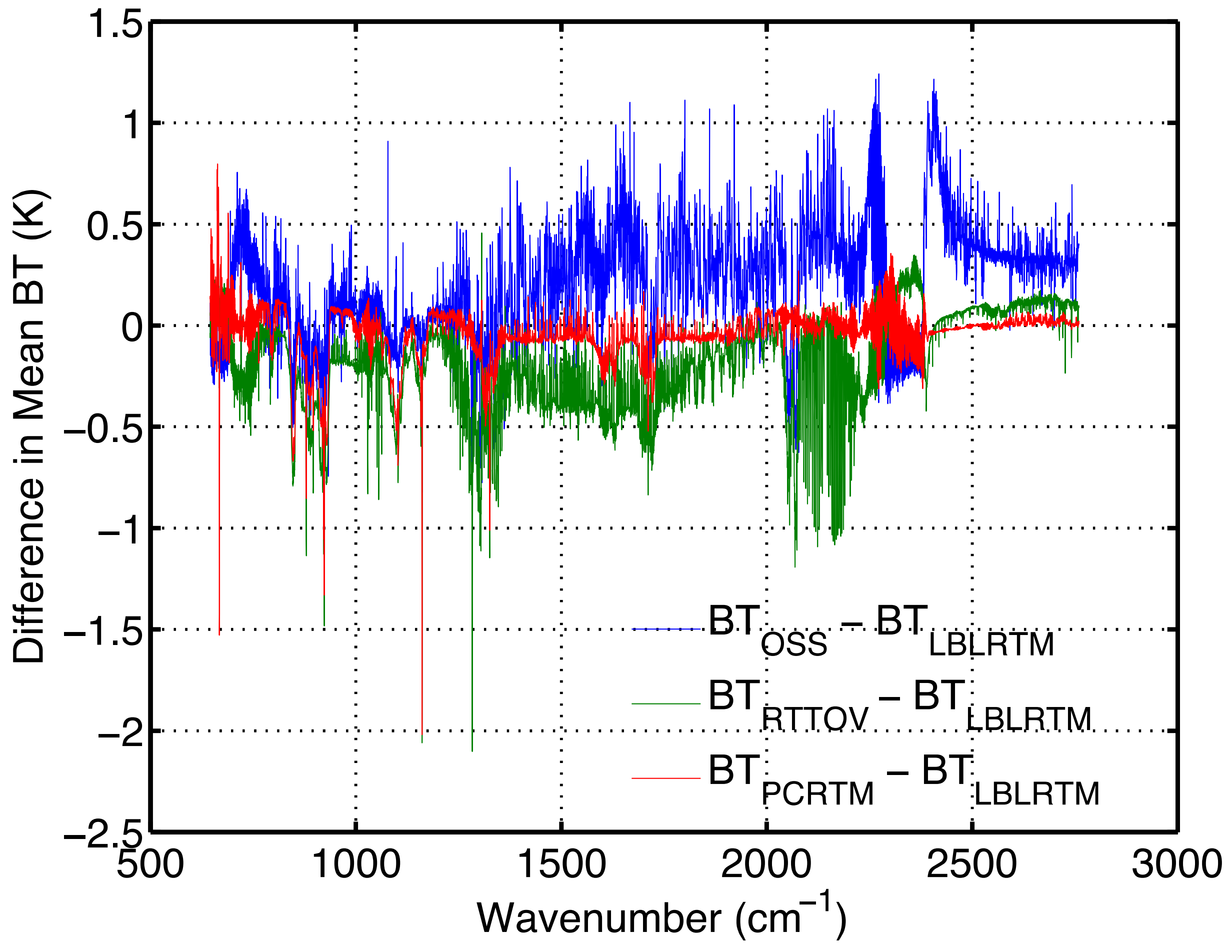
Typical Atmospheric State Vectors



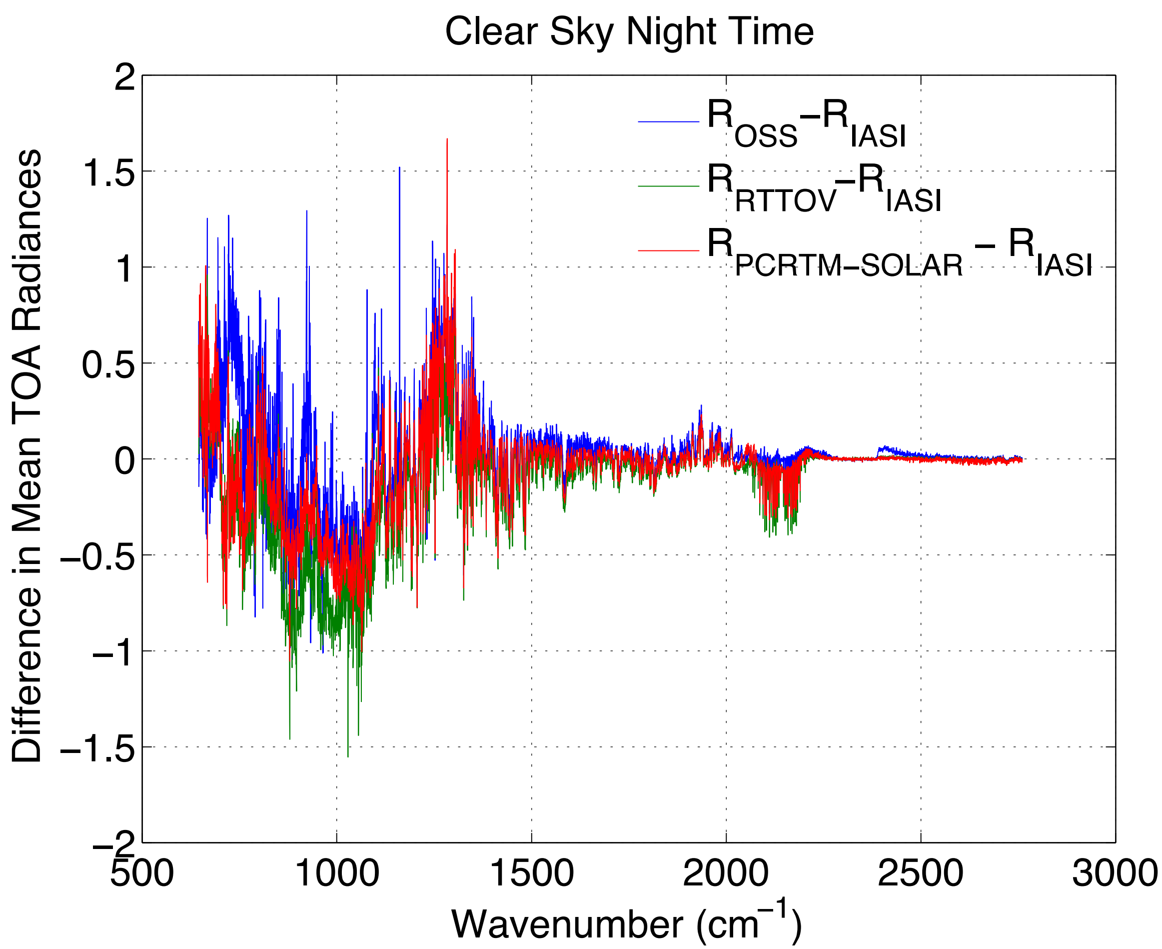
Typical Results



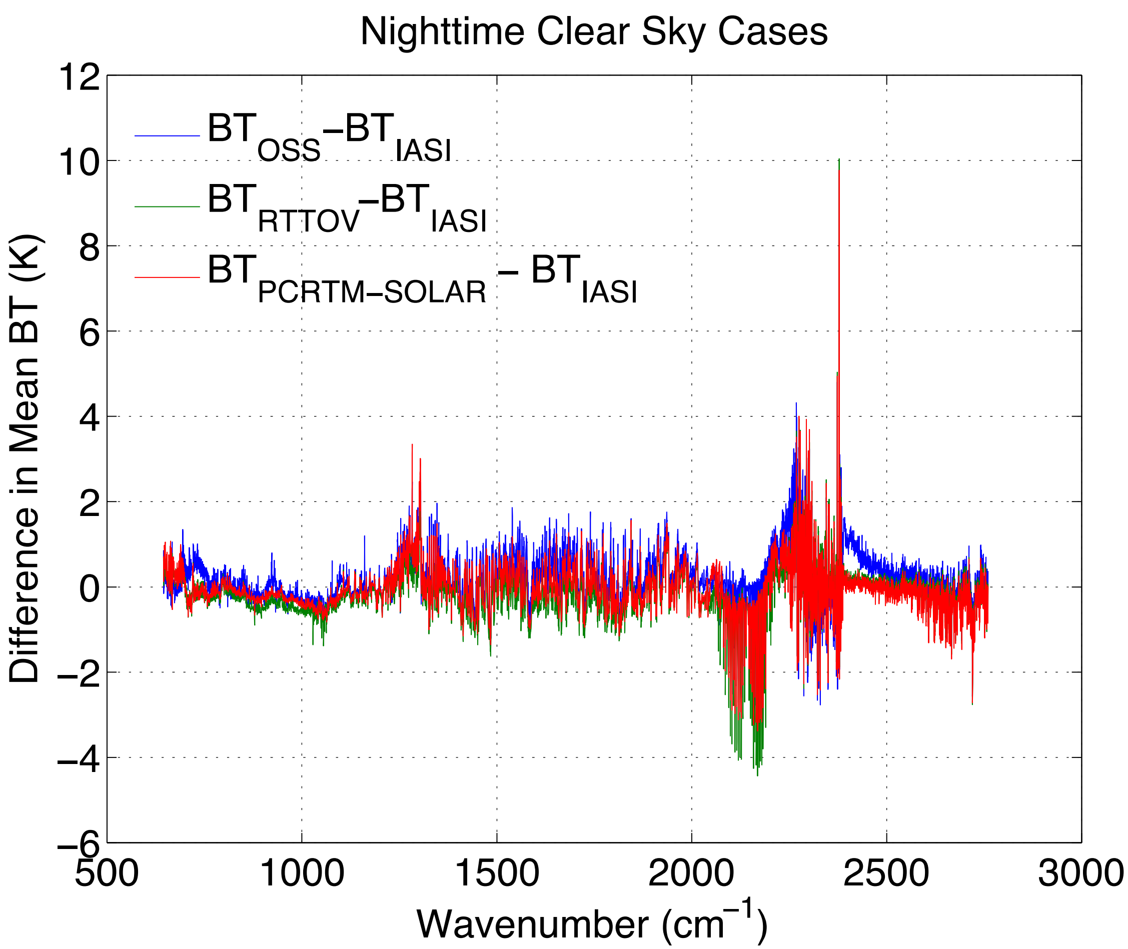
Compare with LBLRTM 12.2



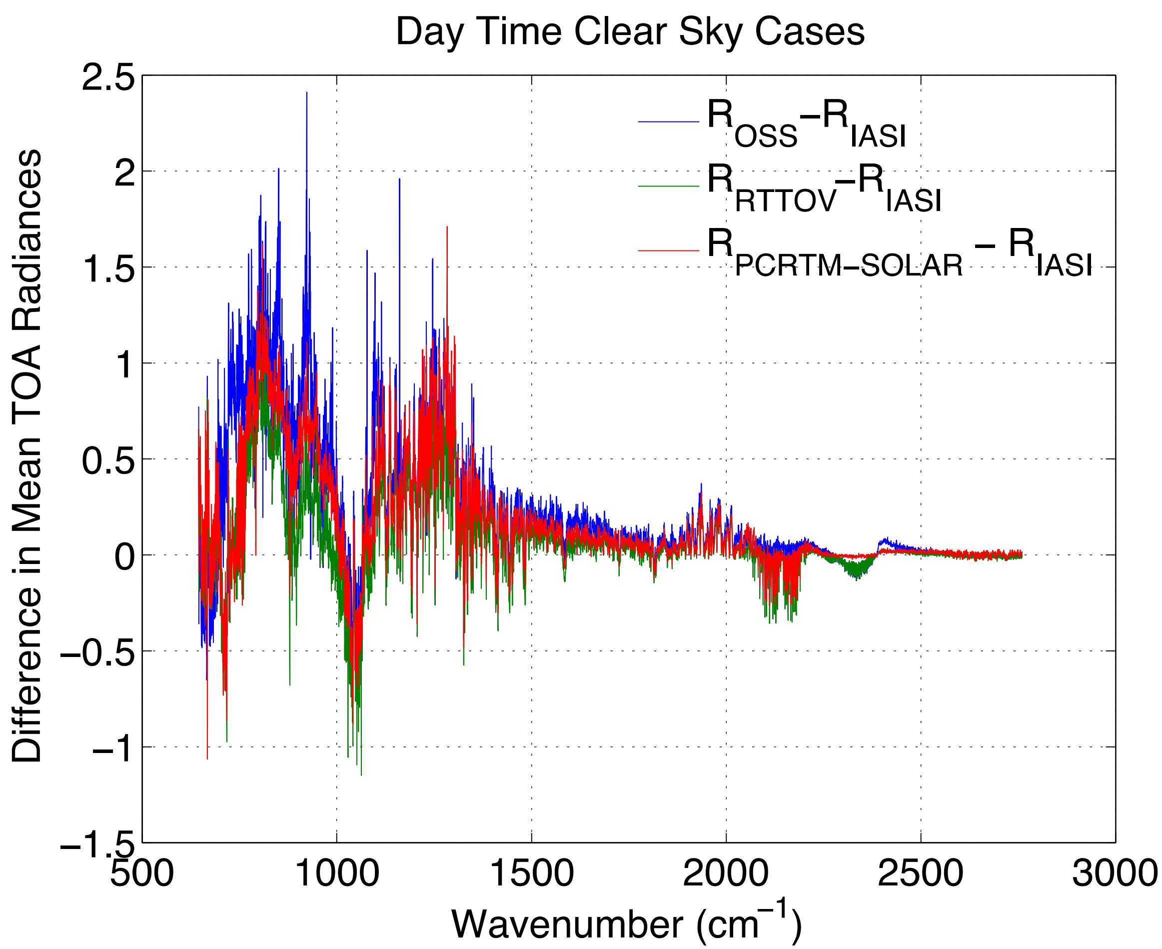
Compare with IASI Measurements



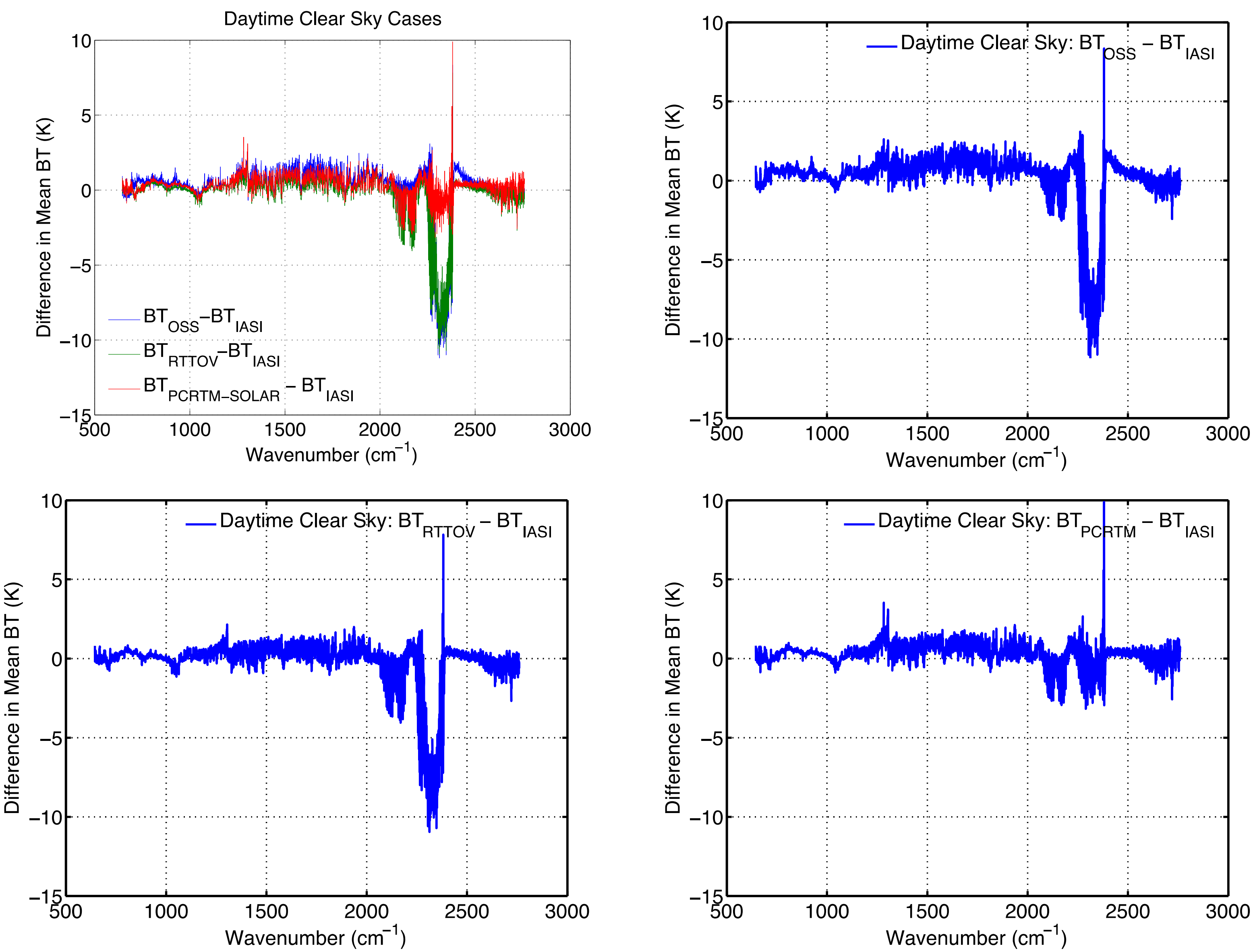
Compare with IASI Measurements



Compare with IASI Measurements



Compare with IASI Measurements



Conclusion

- Robust cloud/aerosol LUTs were generated using modified DISORT.
- Solar spectral reflection contribution was added to previous PCRTM model. We trained the data for instruments IASI, NASTI, CrIS, AIRS, and SHIS using the new data. New EOFs and PC scores were obtained for these instruments.
- The trained results were used for IASI retrieval validation. The simulated results were excellently agreed with the observations.
- The results from the new PCRTM_Solar were comparable to those obtained from LBLRT v12.2, RTTOV v11.2, and OSS software. In the high wavenumber range beyond 1800 cm^{-1}, our results were better since solar contribution was included in our model.